Galactic Factories of CRs: Understanding CRs through gamma-ray observations

Emma de Oña Wilhelmi, DESY-Zeuthen & ICE (CSIC/IEEC)
CRs Origin & Propagation: Connecting Galactic Structures

- Basic Component of the ISM: Matter, GCRs and GMF
- GCRs are dynamically important in the Galaxy
- Dynamic balance processes triggers instabilities in the Galaxy structure

\[
\omega_{\text{CR}} \approx 1 \text{ eV/cm}^3
\]
\[
\omega_B = \frac{B^2}{8\pi} \approx 1 \text{ eV/cm}^3
\]
\[
\omega_{\text{turb, gas}} = \rho_{\text{gas}} v_{\text{turb}}^2 \approx 1 \text{ eV/cm}^3
\]
CRs Origin & Propagation: Connecting Galactic Structures

[Diagram showing the relationship between Cosmic Rays, Magnetic Field, Matter, and Confinement]

Orion B Herschel © ESA
SFRs AKARI © JAXA
SNRs
PWNe
Compact Objects

Galactic Factories of CRs | Emma de Oña Wilhelmi, Dec 2019
**CRs Origin & Propagation: Connecting Galactic Structures**

Perseus (ALLWISE) + Fermi LAT contours (EdOW, Yang, in preparation 2019)

Westerlund 2 (DSS2 + Fermi LAT contours (Yang, EdOW et al 201)

RX J1713.7-3946 HESS

Orion B Herschel © ESA

SFRs AKARI © JAXA

Gamma-ray

SNRs

PWNe

Compact Objects
CRs Origin & Propagation: Where & How?

Question since 1912: what is the origin of Cosmic Rays?

**Spectrum of CRs**

- Extends over 32 orders of magnitude
- Below ~3 PeV CRs are believed to be of Galactic origin
- Luminosity of Galactic CRs $L_{CR} \sim 10^{41}$ erg/s
- Where are PeV CRs accelerated?
CRs Origin & Propagation: Where & How?

Who is powering the CRs?

CR Energetics

- Energy Density of CRs $u_{CR} \sim 1 \text{ eV/cm}^3$
- Volume of the Galaxy $V_{gal} = \pi R_{disk}^2(2h) \sim 3 \times 10^{11} \text{ pc}^3 \sim 10^7 \text{ cm}^3$
- Luminosity $L = u_{CR} \times V_{gal} / t_{CR}$

- CR confinement time (nuclear abundance) $t_{CR} \sim 10^7 \text{ yrs}$: 
  $L = u_{CR} \times V_{gal} / t_{CR} = 5 \times 10^{40} \text{ erg/s}$

- Isotropic in the Galaxy
  Homogeneity requires $t_{recu} < < 10^7 \text{ yrs}$ (or continuous injection?)

We need accelerators that can provide the right energy budget, up to PeV energies, at the required rate to make the distribution homogeneous.
CRs Origin & Propagation: Where & How?

Who is powering them

Aartsen et al (IceCUBE) 2017

Hillas Plot

Standard preliminaries

✓ \( L = u_{CR} \times V_{gal}/t_{CR} = 5 \times 10^{40} \) erg/s
✓ Homogeneity
✓ Up to PeV energies

Confinement condition
necessary condition but not determining

\[ R_L (= E/qB) < R \implies E_{max} = \Gamma qBR \]
CRs Origin & Propagation: Where & How?

Who is powering them

Supernova Remnants

- SNe rate is ~2-3 per century
- Explosion energy $E_{\text{kin}} = 10^{51}$ erg
- $L_{\text{SN}} = 10^{51}/\tau_{\text{recu}} = 6 \times 10^{41}$ erg/s
- $V_{\text{sh}} > 10^3$ km/s
  $\Rightarrow E_{\text{max}} \sim B^{-1/2} V_{\text{sh}}$

Stellar Clusters

- $L \sim 10^{38-39}$ erg/s
- Operating for few $T = \text{Myrs}$
- $W_p = fLT \sim 3 \times 10^{52}$ erg
- Accelerate CRs in the interacting wind or superbubbles
- Large Shock velocities

Others? Galactic Center

- Outburst-like event? $E_{\text{kin}} \sim 3 \times 10^{54}$ erg
- Slow outflows? $L_{\text{IR}} \sim 1.6 \times 10^{42}$ erg/s

L = $u_\text{CR} \times V_{\text{gal}}/t_{\text{CR}} = 5 \times 10^{40}$ erg/s
- Homogeneity
- Up to PeV energies
CRs Origin & Propagation: Where & How?
Is it really a featureless power-law up to a few PeV?

- More than one accelerator class?
- Effect of the CR propagation?

Aartsen et al (IceCUBE) 2017

\[ E^{2.7} \phi(E) \text{ GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

\[ E \text{ (GeV)} \]

- PAMELA
- AMS02
- ATIC
- CREAM
- CALET
- DAMPE
- NUCLEON

Softening
Hardening
CRs Origin & Propagation: Where & How?
Where do they come from? Anisotropies

At low energies (>100 GeV) the CR flux is compatible with isotropy
At higher energies, CR should drift slowly out in the Galaxy -> Anisotropies?

\[ \delta = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{I_1}{I_0}. \]

\[ 10^{-4} \leq \delta \leq 10^{-3}, \text{ for } E \leq 10^{15} \text{ eV} \]
CRs Origin & Propagation: Where & How?
Propagation in the Galaxy

- According to how long they live in the Galaxy:
  \[ \tau = \frac{h^2}{2D} \approx 8 \times 10^6 \text{yr} . \]
  \[ \frac{dN}{dE} \sim \dot{\gamma}/D(E) \sim E^{-(\alpha + k\delta)} \text{ k=3/2, 1} \]
  \[ D(E) = D_0(E/E_0)^\delta , D_0 \sim 10^{28-30} \text{ cm}^2\text{s}^{-1} \]
  \[ t_{\text{recu}} << 10^7 \text{ yrs or Energetic outburst } t > 10^7 \text{ yrs} \]
CRs Origin & Propagation: Where & How?

Propagating in the Galaxy

• According to how long they live in the Galaxy:

$$\tau = \frac{E^2}{2D} \approx 8 \times 10^6 \text{yr}.$$  
$$\frac{dN}{dE} \sim \dot{Q}/D(E) \sim E^{-(\alpha + k\delta)} \quad k=3/2, 1$$

$$D(E) = D_0(E/E_0)^\delta, \quad D_0 \sim 10^{28-30} \text{cm}^2\text{s}^{-1}$$

$$t_{\text{recu}} << 10^7 \text{yrs} \text{ or Energetic outburst } t > 10^7 \text{ yrs}$$

• From their propagation

$$w_{CR}(E,r) = \frac{Q_{\text{source}}(E)}{4\pi D(E)} \frac{1}{r}$$

• Tracer = > Gamma-rays or neutrinos

\[V_e \quad + \quad V_T\]

\[p_{CR} \quad + \quad p_m \quad \rightarrow \quad \pi^0 \quad + \quad \pi^\pm \quad + \quad \pi^\mp \quad + \quad \pi^0 \quad + \quad \pi^\pm \quad + \quad \pi^\mp \]
CRs Origin & Propagation: Connecting Galactic Structures

Studying CRs through their radiation imprints

CRs propagate from the accelerator, loosing energy by different means:

- **Synchrotron**: Need magnetic field $\Rightarrow$ Radio/X-ray Synergies
- **Inverse Compton**: Need soft FIR, NIR, CMB photon fields
- **Bremsstrahlung**: Need dense media

![Graph showing energy distribution of electrons](image)
CRs Origin & Propagation: Connecting Galactic Structures

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The cooling times has strong implications on the CRs propagation (and source size):

\[
T_{\text{syn}} \sim 400 \, B \, uG^{-2} \, E_{\text{TeV}}^{-1} \, \text{yrs}
\]

\[
T_{\text{IC}} \sim 7 \times 10^3 \, \omega_0^{-1} \, E_{\text{TeV}}^{-0.7} \, \text{yrs}
\]

\[
T_{\text{pp}} \sim 1 \times 10^{15} \, n^{-1} \, \text{s} \, (\sim 50 \, \text{Myrs})
\]
CRs Origin & Propagation: Connecting Galactic Structures

Studying CRs through their radiation imprints

\[ R = 2\sqrt{D \, t} \]

- **Proton-Proton**
  - \( B = 100 \mu G \)
  - \( n = 5 \times 10^3 \text{ cm}^{-3} \)

- **Inverse Compton**
  - \( B = 10 \mu G \)

- **Synchrotron**
  - \( B = 100 \mu G \)

Galactic Factories of CRs | Emma de Oña Wilhelmi, Dec 2019
CRs Origin & Propagation: Connecting Galactic Structures

Studying CRs through their radiation imprints

Proton-Proton

Accelerators?

Synchrotron

Size (pc)
CRs Origin & Propagation: Connecting Galactic Structures

Studying CRs through their radiation imprints

Proton-Proton

Accelerators?

Synchrotron

Large Structures in Gamma-rays

300 pc
Prior: is the CR spectrum in our Solar System special?

Space barometers: Giant Molecular Clouds

© Fermi LAT
Prior: is the CR spectrum in our Solar System special?

Space barometers: Giant Molecular Clouds

1/ Looking at the average galactic emission:
Linear correlation between gamma-ray intensity (0.1-10 GeV) and atomic gas column density
=> the flux of CRs within 1 Kpc is consistent with 10% with the one measured in Earth
Prior: is the CR spectrum in our Solar System special?

Space barometers: Giant Molecular Clouds

2/ Looking at clean environments – Isolated large Molecular Clouds as Barometers:

Example of Giant Molecular Cloud (GMC):

**Orion B**

\[ \mathbf{p}_{CR} + \mathbf{p}_m \rightarrow \pi^0 + X + \ldots + \pi^\pm \]

\[ Y + Y \]
Prior: is the CR spectrum in our Solar System special?

**Space barometers: Giant Molecular Clouds**

2/ Looking at clean environments – Isolated large Molecular Clouds as Barometers:

<table>
<thead>
<tr>
<th>#</th>
<th>Region</th>
<th>Mass (Dust / CO)</th>
<th>Distance [pc]</th>
<th>b [°]</th>
<th>M/d^2 [10^5 M☉/kpc^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ρ Oph</td>
<td>0.12 / 0.06</td>
<td>105</td>
<td>356°</td>
<td>18°</td>
</tr>
<tr>
<td>2</td>
<td>Orion B</td>
<td>0.75 / 0.05</td>
<td>500</td>
<td>205°</td>
<td>-14°</td>
</tr>
<tr>
<td>3</td>
<td>Orion A</td>
<td>1.2 / 0.80</td>
<td>500</td>
<td>213°</td>
<td>-18°</td>
</tr>
<tr>
<td>4</td>
<td>Mon R2</td>
<td>1.1 / 0.80</td>
<td>850</td>
<td>214°</td>
<td>-12°</td>
</tr>
<tr>
<td>5</td>
<td>Taurus</td>
<td>0.30 / 0.23</td>
<td>140</td>
<td>170°</td>
<td>-16°</td>
</tr>
<tr>
<td>6</td>
<td>R CrA</td>
<td>0.01 / 0.01</td>
<td>150</td>
<td>0.5°</td>
<td>-18°</td>
</tr>
<tr>
<td>7</td>
<td>Channel</td>
<td>0.11 / 0.09</td>
<td>215</td>
<td>380°</td>
<td>-10°</td>
</tr>
<tr>
<td>8</td>
<td>Perseus O182</td>
<td>0.41 / 0.3</td>
<td>350</td>
<td>158°</td>
<td>-20°</td>
</tr>
</tbody>
</table>

- E > 20 GeV: good agreement with CR spectrum measured at Earth
- Low energy part shows differs from cloud to cloud
- Related to different environment: local acceleration, low CR penetration effects, modulation effects?

We know reasonably well the CR in our Galaxy
Active Clouds

When a massive cloud a deviation wrt the local CR, indicates an acceleration in the vicinity!
Active Clouds

Diffuse emission correlated with molecular cloud distribution
→ the ratio of the TeV flux to the gas density provides the CR density
Active Clouds

Diffuse emission correlated with molecular cloud distribution

→ the ratio of the TeV flux to the gas density provides the CR density

Gamma-ray luminosity measurement in several regions
- Use of cloud mass measurements gas density from CS (CO, HCN)
- $W_{\text{CR}} \sim 10^{49}$ erg
Active Clouds

- First evidence of CRs accelerated to PeV energies (diffuse emission)
- Accelerator? a clear cutoff on the point source in the Galactic center (HESS J1745-290)

The injection time should be larger than the escape one:

$$\Delta t \geq t_{\text{diff}} \approx \frac{R^2}{6D} \approx 2 \times 10^3 \left(\frac{D}{10^{30} \text{ cm}^2\text{s}^{-1}}\right)^{-1} \text{ yr},$$

$$Q_p (\geq 10 \text{ TeV}) \approx 4 \times 10^{37} \left(\frac{D}{10^{30} \text{ cm}^2\text{s}^{-1}}\right) \text{ erg/s}.$$}

Rather modest injection for thousands of years:
- Galactic center?
- Stellar clusters in the inner region?  

HESS Col. 2016
Star Formation Regions
Can SFR accelerate PeV CRs?

Stellar Clusters: Energy reservoir $\sim 10^{38-39}$ erg over ages of $T\geq 10^6$ years

Several large-scale gamma-ray emission detected with LAT
- The large size & morphology disfavor a unique leptonic accelerator:
  - Large $U_{ph}$ would result in a peaked emission towards the cluster
  - Electrons can only diffuse up $\sim 30$ pc
- Use of cloud mass measurements gas density
  CO:CfA 1.2 mm-wave Telescope & HI:LAB Survey
- Derive the CR distribution & spectrum

$$W_{tot} = fL_0T_0 = 3 \times 10^{52} fL_{39}T_6 \text{ erg}$$

<table>
<thead>
<tr>
<th>Source</th>
<th>Cygnus Cocoon</th>
<th>CMZ</th>
<th>WA &amp; Cocoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension (pc)</td>
<td>50</td>
<td>175</td>
<td>60</td>
</tr>
<tr>
<td>Age of cluster (Myr) $^{39}$</td>
<td>3–6</td>
<td>2–7</td>
<td>4–6</td>
</tr>
<tr>
<td>Kinetic luminosity, $L_{kin}$ of cluster (erg s$^{-1}$)</td>
<td>$2 \times 10^{38}$ (ref. 17)</td>
<td>$1 \times 10^{39}$ (ref. 40)</td>
<td>$1 \times 10^{39}$ (ref. 41)</td>
</tr>
<tr>
<td>Distance (kpc)</td>
<td>1.4</td>
<td>8.5</td>
<td>4</td>
</tr>
<tr>
<td>$\omega_{b}$ (&gt;10 TeV) (eV cm$^{-3}$)</td>
<td>0.05</td>
<td>0.07</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Star Formation Regions

Can SFR accelerate PeV CRs?

Example: Cygnus Cocoon.
Star Formation Regions
Can SFR accelerate PeV CRs?

The spectra (of some of them) extends to high energies
With remarkably similar shape and spectral index (2.2)
No indication of energy cutoff (with the available statistics)
Proton spectrum described with:
\[ E^{-2.3} \exp(-E/E_0) \text{ with } E_0 = 0.2 \ (1), \ 0.5 \ (2) \]

=> For Kolmogorov-type turbulence, \( D(E) \propto E^{1/3} \), we arrive at a ‘classical’ \( E^{-2} \)-type acceleration spectrum.
Star Formation Regions
Can SFR accelerate PeV CRs?

The CR proton radial distribution follows a 1/r line (>10 TeV) (for the Cygnus Cocoon we extrapolated from LAT energies)

Exceeding the local CR by a factor of 10 (from AMS)

We parametrized the CR density as:

\[
\omega(r) = \omega_0(r/r_0)^{-1}
\]

\[
W_p = 4\pi \int_0^{R_0} \omega(r)r^2 \, dr \\
\approx 2.7 \times 10^{47} (\omega_0/1 \text{ eV cm}^{-3})(R_0/10 \text{ pc})^2 \text{ erg}
\]
Star Formation Regions

Estimation of the CR density and their transport

We define R as the extension of the source (50 and 300 pc), or more conservatively, the maximum given by the diffusion condition:

\[ R_D = 2 \sqrt{T_0 D(E)} \approx 3.6 \times 10^3 (D_{30} T_6)^{1/2} \text{ pc} \]

Since \( W_{\text{CR}} \) cannot be larger than \( W_{\text{tot}} \) =>

\[ f(\geq 10 \text{ TeV}) \approx 1 w_0 D_{30} L_{39}^{-1} \]

Measuring the Local diffuse coefficient:

if \( f=10\% \) => \( D \sim 10^{28} \text{ cm}^2 \text{ s}^{-1} \)

Halos as large as 300 pc and with a density still 2 order of magnitude larger than the local CR density
Supernova Remnants

The standard paradigm

CR Standard Paradigm $E_{\text{kin}} \sim 10^{51}$ erg/SN, rate=2-3 century $\Rightarrow$ 10% to sustain the $10^{41}$ erg/s CR
Supernova Remnants

The standard paradigm

\[ E_{\text{kin}} \sim 10^{51} \text{ erg/SN}, \text{ rate}=2-3 \text{ century} \Rightarrow 10\% \text{ to sustain the } 10^{41} \text{ erg/s CR} \]

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<td></td>
<td>@S. Funk</td>
</tr>
</tbody>
</table>
Conclusions

Factories of CRs

• We have established that (at least a large fraction of) the bulk of CRs (GeV) accelerates in SNRs:
  ✓ Detection of many GeV & TeV SNRs
  ✓ Magnetic field amplification in shell
  ✓ Spectral energy distributions (pion decay)

BUT

• We don’t have any proof of SNR accelerating CRs to PeV (PeVatrons)
• We see at least one PeVatron in the Galactic center region:
  The emission is hardly compatible with impulsive (SNR) acceleration of CRs
• The Galactic Center alone could have some past active phase and fill the Galaxy (and Fermi bubbles!)
• The Galactic Center region hosts 15% of the stellar activity in our Galaxy
  => Stellar Cluster could accelerate CRs
Conclusions

Factories of CRs

- Stellar Cluster are potentially good sources of PeV CRs
- We observe large ~degree sources in dense regions:
  - The spectrum is compatible with hadronic emission
  - The 1/r profile favors diffusive propagation of CRs vs advecting in winds or single burst-like
  - Stellar cluster can be extremely efficiency in accelerating CRs.
- Still to many things to investigate! How many populations of Galactic sources are there?
  ➔ We need better data and more photons – Time for CTA